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Propagation of sub-picosecond laser pulses through a preformed plasma

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Abstract

Measurements of transmitted light, 90 degree sidescattered light, and FROG traces have demonstrated relativistic filamentation of 600-fs laser pulses in a preformed, fully-ionized plasma.

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The development of high intensity lasers has led to the possibility of observing relativistic effects when a laser pulse interacts with a fully ionized plasma. The propagation of high intensity laser pulses through a fully ionized plasma has practical applications for compact x-ray lasers [1,2], laser-plasma-based particle accelerators [3], and advanced inertial confinement fusion schemes [4]. The relativistic filamentation instability [5] can lead to modifications of the propagating pulse by spatially modulating the laser intensity transverse to the direction of propagation; growth of the instability can lead to spreading of the beam as the result of the density modulation set up by the filamented ponderomotive force. The beam propagation needs to be understood before further nonlinear effects are investigated [6,7]. Previous experimental studies of high-intensity laser pulses have employed neutral gases which are ionized by the propagating pulse [8]. That technique is limited by technical constraints to relatively low electron densities ($\leq 10^{19}$ cm^{-3}) and introduces the possibility of the modification of the propagation behavior by the formation of an ionization front at the leading edge of the pulse [8].

In this Letter, we describe an experiment [9] in which a high intensity (up to 5 x 10^{18} W/cm^2), 600-fsec laser pulse propagates through a fully-ionized preformed plasma of substantial density (up to $0.5n_c$). When the laser intensity, I_L, and plasma density, n_e are sufficiently low such that relativistic filamentation does not grow, the pulse channels through the plasma. As I_L or n_e is increased, we observe the onset of relativistic filamentation, in which the beam breaks up into multiple hot spots, as opposed to whole-beam self-focusing, by analysing the light transmitted through the plasma and by 2-D pictures of the sidescattered laser light. If the plasma density or the laser intensity is high enough, the beam breakup occurs before the pulse reaches the peak plasma density. Along with the beam breakup, we observe time-dependent spectral modulation of the laser pulse transmitted through the plasma using a frequency-resolved optical gating (FROG) diagnostic. In the early part of the pulse we observe a spectral red-shift, consistent with electrons being moved out of the beam path, followed by a spectral blue shift, signaling the collapse of the channel.

The experiment was performed using the Janus laser facility at Lawrence Livermore National Laboratory. One beam of the laser produced a 0.53 μm wavelength, 45 J, 1.3 ns long, nominally square laser pulse that irradiated a 0.5 μm thick polypropylene exploding foil target (CH_2) which is supported by a 75-mm-thick Mylar washer. This beam is focused with an f/4 lens to a 400 μm diameter spot. After the plasma forming pulse has burned through the target and the peak density has decayed below n_c, a second, interaction pulse counterpropagates relative to the plasma forming beam through the plasma. This pulse has a central wavelength of 1.053 μm with a bandwidth of 1.4 nm, and is compressed to a FWHM pulse width of ~ 600 fs. The 6.5 cm diameter beam is focused by a 30 cm focal length off-axis parabola to a focused spot with a FWHM diameter of 12 μm which was measured with an equivalent plane imaging system. At the highest input energies (6 J) the maximum intensity at best focus is ~ 5 x 10^{18} W/cm^2.

Light that is transmitted through the plasma is collected by the focusing lens of the plasma forming lens; 50% of the light goes to an energy calorimeter and 50% goes to a single-shot FROG diagnostic [10] which records the laser spectrum versus time with 10 fs resolution. The target plasma density distribution was measured by a folded wave interferometer throughout the experiment. The probe beam for the interferometer was 0.35 μm wavelength, 600 fs in duration, and was timed to within 50 ps of the arrival of the interaction pulse at the target. We also imaged the sidescattered 1.053 μm light transverse to the propagation direction of the ps pulse in order to locate the position of the maximum laser intensity.

The onset of relativistic filamentation is shown quite clearly in the scaling of the collected transmitted energy with the incident beam energy (see Fig. 1). As we found in earlier, 100 ps experiments [11], filamentation can result in the spraying out of the transmitted light to angles much larger than the vacuum propagation angle. In Fig. 1, we see that at low laser intensities, the transmitted laser energy equals the incident energy. Above an intensity of 10^{18} W/cm^2, the percentage of transmitted light is less as the filamentation instability increases. Varying the peak density changes the laser intensity at which the inflection point occurs. For a peak density of $0.1n_c$, the transition occurs near 0.15 J, while for a peak density of $0.05n_c$, it occurs near 0.7 J. The maximum amount of light backscattered into the parabola was 10% and cannot account for the transmission behavior.

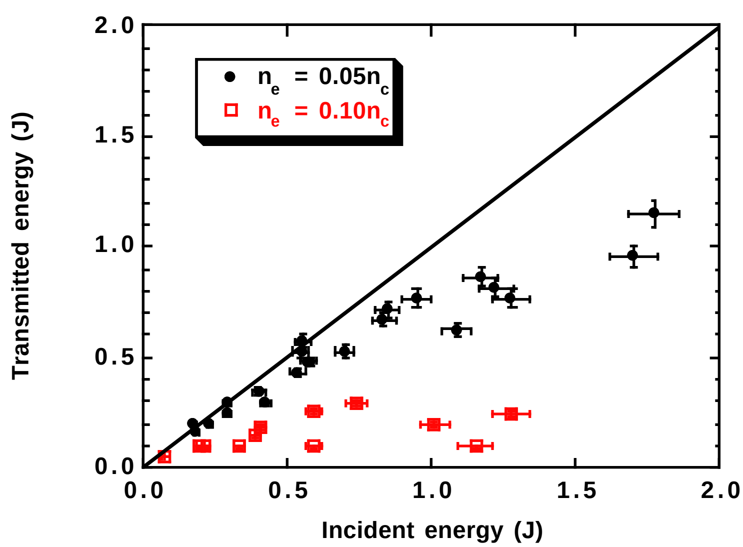

FIGURE 1. Measured energy transmitted through the plasma as a function of the incident energy for two different peak plasma densities.

The power at which the transition occurs in Fig. 1 is greater than the predicted critical power for relativistic self-focusing:

$$P_c = 17(n_c/n_e)\ \mathrm{GW}. \quad (1)$$

Substituting the measured peak densities into this equation gives critical powers of P_c = 340 GW or E_c = 200 mJ for $n_e = .05n_c$, and P_c = 170 GW or E_c = 100 mJ for $n_e = .1n_c$. The threshold energies are higher than those given by the theory probably because the theory is linear, whereas in the actual experiment the high intensity pulse can depress the background density.

We used filtered, high-speed infrared film to record the light outside the collecting lens. and show that as the energy was increased, the light sprayed to larger angles consistent with the observed decrease in the transmitted energy [11]. Most of the sprayed light has wavelengths close to the fundamental laser wavelength and the contributions from SRS are small. This result is consistent with the simulations of Ref. 12 which predict a 20% reduction of transmitted light due to SRS absorption and scattering. It has also been pointed out [13] that SRS will not occur in evacuated channels. These results are consistent with previous experiments [14], in which a single pulse interacts with a gas jet, have observed that as they increased the gas fill pressures (higher electron densities) they observed the reduction of the forward SRS anti-Stokes feature to the detection noise level which was accompanied by the exponential increase of the transmitted laser light, which they attributed to self-focusing and ionization induced refraction (which cannot occur in our experiment).

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